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QUANTITATIVE THERMAL IMAGING USING LIQUID CRYSTALS

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ABSTRACT

A detailed knowledge of surface temperatures is vitally important in many fields of science and engineering. Thermochromic liquid crystals have become widely accepted over the past decade as a simple, low-cost, and accurate tool for temperature measurement, but their potential in biological surface temperature monitoring or heat production, or biomechanics, has not been fully exploited. In this paper, the principles and practice of using liquid crystal thermography for noninvasive temperature measurement are discussed. Types of liquid crystal materials, their application to surfaces, chromatic interpretation, and associated advantages and limitations are summarized. Finally, the application of liquid crystals to particular fields of interest in biomedical engineering is reviewed and potential applications are identified. Based on this review, the suitability of using liquid crystals in medical applications is assessed.

Key Words temperature; liquid crystals; thermography; skin.

1 BACKGROUND

Thermography is the visual representation of the variations of a surface temperature. Ideally, a thermographic technique should yield a qualitative and quantitative, instantaneous thermogram with a high level of temporal, thermal, and spatial resolution. There are several different techniques available for temperature measurement, both noncontact and contact, such as infrared thermography, and thermocoupling, respectively. Infrared thermography equipment is expensive and when a detailed temperature map is required, so is extensive thermocoupling. However, for detailed information at low temperatures, liquid crystal thermography (LCT) can provide a highly sensitive, inexpensive, reliable, and repeatable indication of temperature.

The use of liquid crystals to determine the temperature distribution on a surface is by no means a new idea. It is, however, only in recent years that materials suitable for many measurement applications have become readily available. There is now a reasonable amount of archived literature which renders the technique promising in many science and engineering disciplines. Much of the work during the 1960s and early 1970s related to the development of liquid crystal materials and the feasibility of their use. The latter years have focused on their potential applications. Over 10% of publications identified in a comprehensive literature survey of applications of LCT (see Appendix A) refer to medical or clinical applications. These include the use of liquid crystals in evaluating and developing equipment (such as surgical probes) and assistive devices, monitoring processes, investigating the behavior of fluids, and direct application to the skin. Indeed, over 5% of the work directly addresses the use of liquid crystals in aiding medical diagnosis by monitoring skin temperature. Since many local medical problems possess a temperature different from the surrounding tissue, this is an important diagnostic aid. Applications include disease diagnosis; fever indication; vein location and localized changes in blood flow; corneal monitoring; stress and anxiety indication; as well as dental, chiropractic, and veterinary applications. Needless to say, despite the potential of cholesteric liquid crystals, indicated by the number of publications to date, the technique is still not widely exploited. In this paper the principles and practice of liquid crystal thermography are presented. Liquid crystals, their history, application to a surface, temperature ranges, bandwidths, advantages, and limitations have been summarized. Their chromatic interpretation is also addressed. Finally, some publications on the applications of liquid crystals are briefly reviewed and, based on these, the suitability of using liquid crystals for biomedical applications is assessed.

2 LIQUID CRYSTALS AND THEIR APPLICATION TO SURFACES

Like many organic compounds, liquid crystals are anisotropic fluids. They adopt an intermediate structure between the solid phase and the isotropic

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phase, known as the mesomorphic phase, and exhibit the optical properties of crystalline solids but the mechanical properties of liquids. Their peculiar color phenomena were first reported toward the end of the last century,[1] and the materials were later named "liquid crystals."[2] They are also known as mesogens, mesomorphs, and mesophases. Since this time, many different formulations of liquid crystals have been identified and the use of temperature-sensitive and temperature-insensitive liquid crystals has been widely investigated by engineers and scientists. Thermotropic liquid crystals (TLC) result from the melting of mesogenic solids. Being thermally active, they possess the required properties for temperature measurement. Many researchers use liquid crystals which, although referred to as cholesteric, are not derivatives of cholesterol and should be referred to as chiral nematics. The physical properties of these classifications are different due to their different chemical compositions:[3] (1) Cholesteric liquid crystals are derivatives of cholesterol and other sterol-related chemicals. (2) Chiral nematic liquid crystals are formulated entirely from nonsterol-based chemicals.

Cholesteric (and chiral nematic) liquid crystals reflect light at a specific wavelength (color) for a given temperature and possess the most suitable optical properties for temperature indication. The liquid crystals have twisted molecular structures that react to changes in temperature by altering their molecular orientation. Their change in phase and associated color response is illustrated schematically in Figure 1. They show colors by selectively reflecting incident white light, depending on the liquid crystal pitch. As their temperature rises through the cholesteric phase, they change to red, and pass through the visible spectrum in sequence. This color change is both reversible and repeatable. The liquid crystal appears colorless below and above this temperature range when in the smectic or isotropic phases of transition. By mixing different cholesteric/chiral nematic compounds, the temperature range over which the pitch of the liquid crystal formulation occurs in the visible part of the spectrum can, to some extent, be controlled. Thus thermal indicators capable of indicating very small or large temperature differences can be manufactured. Single-color (temperature insensitive or shear sensitive) liquid crystals are also available that reflect a single color as the temperature increases. As the liquid crystal changes to its isotropic liquid phase (typically over 0.5°C), it becomes transparent.

The liquid crystal materials have a greasy consistency that can be difficult to work with and that will not dry when applied to a surface. In addition, the perceived color is a strong function of viewing angle. Consequently, they are usually used encapsulated (~10 μm) within a gelatine/gum arabic capsule and suspended in an aqueous liquid to form a paint that dries when applied to a surface.

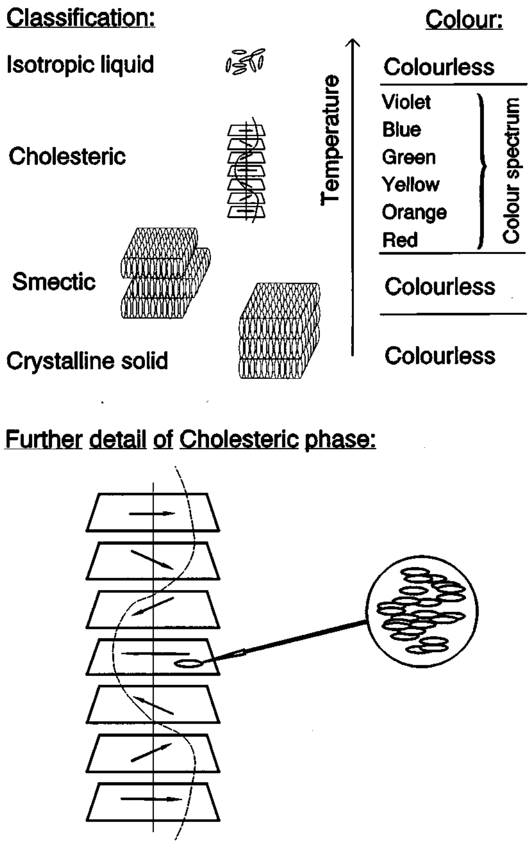

Fig. 1 Phases and associated color response of thermotropic liquid crystals.

The microencapsulation has the advantage of reducing the effect of viewing angle on the perceived color and also extends the life of the formulation, since the liquid crystals degrade due to impurities in the surroundings and exposure to ultraviolet light. Conversely, the capsule wall thickness and size can be difficult to control and the process has a detrimental effect on the temperature response and color play characteristics of the liquid crystals. However, in most applications these factors, or their effects, can be considered negligible. Microencapsulation does, however, significantly reduce the sensitivity to shear stress. Consequently, it is the unsealed cholesteric mixtures that are used for shear stress investigations. The microencapsulated formulations usually contain chiral nematic liquid crystals, but may contain cholesteric crystals, or a combination of both, depending on the required specification.

There are several ways of applying the liquid crystal coating: brush painting, rolling, dipping, spray painting, and screen printing. The last two methods provide the thinnest and most uniform coatings. The thickness and uniformity are important to ensure good response, clarity of the color spectrum, and uniformity of the thermograph. Usually, a layer of liquid crystals is applied over a thin layer of water-soluble black paint which improves the color resolution by absorbing unreflected light. The typical thickness of the combined dry layer, achieved by spraying with an artist's air brush, has been determined by the author to be $<20\ \mu m$. Materials are available with typical temperature ranges varying from −30 up to 120°C with color bandwidths from <1 up to >20°C, depending on the red start temperature. Pre-prepared TLC thermometers usually consist of a series of liquid crystal formulations arranged to change color in sequence as the temperature rises. The resolution of these devices therefore depends on the start temperature and bandwidth of the formulations used.

3 CHROMATIC INTERPRETATION, CALIBRATION, AND ILLUMINATION OF LIQUID CRYSTALS APPLIED TO SURFACES

Until recently, liquid crystal color thermographs were processed only manually, in a similar way to reading a TLC thermometer. This allowed uncertainties to be introduced into the results by human error and individual interpretation of color. For the determination of a single temperature, the yellow or green isotherm is often selected because the human eye is most sensitive to these wavelengths of light at which maximum intensity occurs and because these colors occur over a relatively small temperature range, thus optimizing the spatial and thermal resolution; the color response of the liquid crystals is not linearly proportional to temperature (see Figure 2). Using manual interpretation to read a typical liquid crystal formulation with a bandwidth of a few degrees Celsius can yield temperature measurements to within <1°C.

Spatial resolution depends on the liquid crystal bandwidth and the temperature gradient to which it is exposed and can vary considerably. When a wide bandwidth liquid crystal is used where low temperature gradients prevail, the manual processing technique is satisfactory if only a qualitative indication of temperature or trends in temperature change are required, or if accurate spatial details are not important. However, the method can be time-consuming if a detailed distribution of surface temperature is required. Digital image processing techniques have eliminated this subjective interpretation of color, substantially reducing the time required for the analysis of thermographic data and improving the spatial resolution of the monitored isotherm.

Despite the fact that the excellent potential resolution of thermochromic liquid crystals was established to be considerably better than 0.02°C in the 1970s,[4,5] the majority of image processing systems have been developed relatively recently by engineering departments in an effort to improve the measurement of temperature for convective heat transfer coefficients. Surface temperature information can be obtained automatically by either monochromatic[6–8] or chromatic[9–15] interpretation. Bandpass optical filters can be used to identify a specific temperature or can be selected to indicate an area that lies above or below a specific temperature. In the case of manual analysis or a monochromatic image processing system, calibration of the liquid crystals is usually for a single event; an event temperature which corresponds to a single color and an ambiguity band which corresponds to the first and last appearance of a color. There are various approaches to achieving this calibration either *in situ* (for example, by placing a thin foil thermocouple directly beneath the liquid crystal layer) or by using a calibration apparatus. In practice, the temperature can be resolved to better than 0.1°C using the above processing techniques.

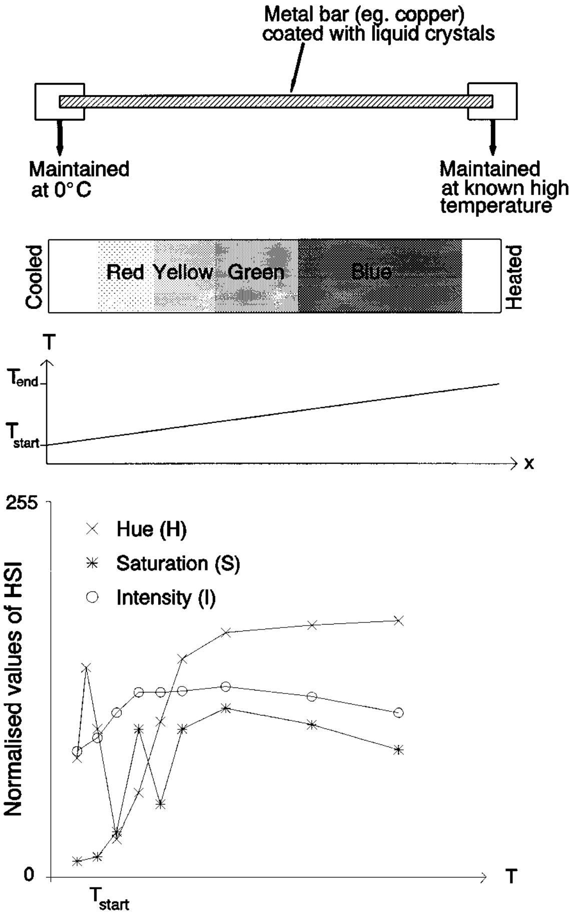

Fig. 2 Calibration of liquid crystals by exposure to a known temperature gradient.

The procedure shown in Figure 2 enables hue, saturation, and intensity (HSI) information to be obtained using wavelength/intensity detectors. Chromatic interpretation relates temperature to hue (wavelength) usually by using red, green, blue intensity (RGB) decomposition. Detailed discussions

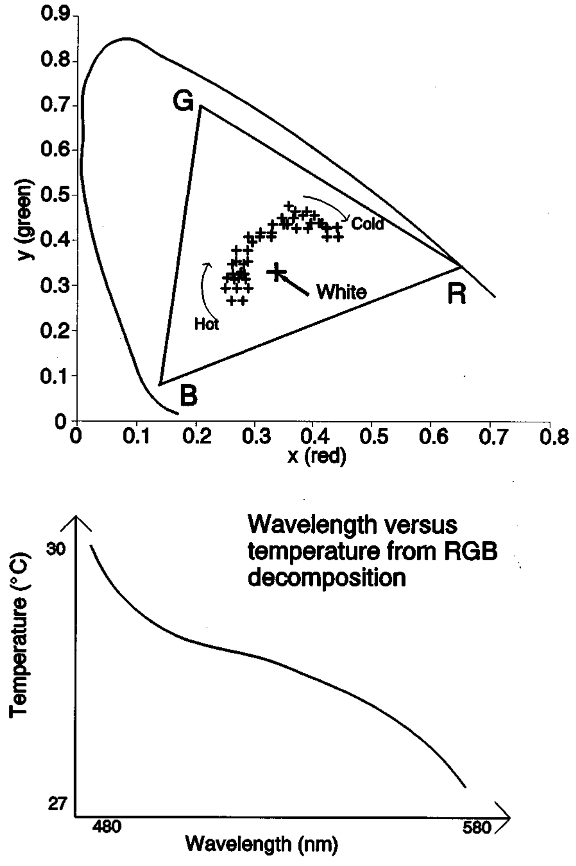

Fig. 3 Typical chromaticity diagram and calibration curve.

of different approaches to HSI/chromatic interpretation and calibration are provided elsewhere.[9–15] In general, the recorded video signal is interpreted by separating it into its RGB components. The resulting information is used to locate a point on the chromaticity diagram, which yields the corresponding wavelength of the signal. Relating this to the calibration curve leads to the corresponding temperature. Figure 3 shows a typical chromaticity diagram and calibration curve. The resolution is much improved with HSI/chromatic interpretation, with better than 0.02°C reported.

Automatic interpretation also improves spatial resolution. For example, a minimum of 512 image pixels may represent a specimen dimension of 150 mm, yielding a spatial resolution of <1 mm.

Since the temperature information gained from LCT is based upon the selective reflection of white light, whatever recording medium is used (SLR camera, video camera, or human eye), it is usually necessary to illuminate the liquid crystal-coated surface, while minimizing background light. This has been achieved in the past using various incandescent or discharge lamps which have since been shown to be inappropriate. Not only can liquid crystals deteriorate (or shift their calibration) with exposure to ambient light but the perceived color of the liquid crystal isotherm depends on the lighting and viewing arrangement, the spectrum of the primary illumination and background light, and the optical properties of the measurement path. In addition, infrared heating would raise the temperature of the measurement surface (unless a cold light source was achieved using filters). Although *in situ* calibration would overcome some of these effects, the ideal calibration method would allow the entire hue-temperature curve to be determined from a single recorded image. Using a point light source, Fergason[16] demonstrated the effect of the lighting and viewing arrangement on the perceived color of the liquid crystals. In a further study, Herold and Wiegel[17] observed that as the angle between the illumination and viewing locations increased, the perceived color of the TLC shifted nonlinearly at constant temperature, but they observed no color shift when viewing and illumination were performed from the same angle. A difference in viewing and illumination distances from the subject, however, appears to have very small effect on the perceived color.[11] Most biomedical applications do not involve perfectly flat surfaces so that some estimate of the measurement uncertainty associated with the viewing and illumination arrangement is crucial if the calibration curve is to be determined from a single liquid crystal image. The above effects have been quantified for a 5°C bandwidth liquid crystal with on-axis lighting and viewing (with cross polarizers).[18] An uncertainty of ±0.25°C for a viewing angle up to ±25 degrees was reported. More recently, effects of viewing angles up to 66 degrees in 3 degree increments have been quantified.[19]

4 MEASUREMENT OF SURFACE TEMPERATURE (INCLUDING SKIN TEMPERATURE): ADVANTAGES AND LIMITATIONS

Human skin temperatures generally lie between 25 and 36°C and are ideally suited to temperature indication by liquid crystals. Usually for direct skin contact, pre-prepared liquid crystal sheets or films in either flexible or nonflexible form (available with or without adhesive) are used.

The response of the liquid crystal sheet will be affected by its thickness. Consequently, in some uses direct application to the surface is preferred, and both unsealed and microencapsulated thermochromic liquid crystal mixtures are available with temperature ranges and bandwidths suitable for this purpose. These can also be applied to preblackened skin, although more convenient flexible blackened sheets coated with liquid crystals are commonly employed.

The temporal response of liquid crystal paints has been reported to be within a few milliseconds.[20] The response depends on the specific formulation of the coating since chiral nematics tend to have a better response than cholesterics. Even when the liquid crystal is sandwiched between an adhesive and Mylar strip, it has been shown to consistently respond faster than electronic skin temperature sensors based on thermistors or thermocouples.[21]

Since the temperature indication of the surface depends on the transfer of heat from the specimen to the TLC sheet by conduction, close contact between the sheet and the surface is essential. This precludes the use of the sheet on rough or nonuniform surfaces, including uneven or broken skin. In addition, the uneven surface leads to problems in interpretation of the reflected colors due to the variation in viewing angle. When a large area is to be studied, the technique is limited to components or parts of the body that have only slight curvatures. In medical practice, liquid crystal flexible sheets have been mounted on air pillows stretched over a frame to ensure good thermal contact (e.g. Ref. 22). On release from the skin, the surface returns to its original flat state. The temperature distribution is recorded by flash photography.

Some applications will be affected by the insulation effect of the liquid crystal sheet that shields the usually exposed surface from the environment. The thermal conductivity of the liquid crystal coating is similar to that of acrylic (0.2 W/mK),[23] so that effects due to a different thermal resistance can be considered negligible when application is directly onto the surface. This also applies to skin coverage. For this reason, and because transparent acrylic materials are readily available and machinable, they are the most frequently used material for building experimental models. Heat losses due to lateral conduction are also minimized by the low thermal conductivity. Additional sources of error for *in vivo* tests include variations between subjects and local environmental factors affecting the body and skin temperature. In cases of extreme environmental conditions, differences up to 1°C have been reported (e.g. Ref. 22). Dissension among early findings has stimulated a number of independent evaluations of LCT (e.g. Refs. 24–27). Excellent agreement between LCT and commercial thermocouples has been demonstrated in controlled laboratory tests; however, during *in vivo* tests, a hysteresis effect was observed which was attributed to room drafts;[27] the profiles typically differed by 1 °C.

Liquid crystals may be damaged by exposure to certain solvents, greases and acids, although this sensitivity is reduced by encapsulation, so the surface should be clean and free from impurities before the coating is applied. Liquid crystals also deteriorate with exposure to ultraviolet light. However, if the liquid crystal paints, sheets, or coated test specimens are stored in cool, dark conditions, they may be reused, reflecting brilliant colors, for many months.

In summary, LCT is a simple, yet powerful temperature measurement technique. It can offer resolution and responses comparable to alternative techniques, such as infrared thermography, thermocoupling, and mercury-in-glass (MIG) thermometers. It is noninvasive, reversible, repeatable, sensitive, easy to use and can provide an immediate visual indication of surface temperature distributions. Either manual (from photographs or *in situ*) or automated processing can be employed. From a medical point of view, it has the potential to provide a continuous quantitative record of variations in temperature without causing any discomfort. Even using manual interpretation, trends in temperatures could be indicated as opposed to using MIG or electronic thermometers; for example, this would provide a particular advantage over rectal or oral temperatures taken in children.

5 REVIEW OF LCT AS AN INVESTIGATIVE AND DIAGNOSTIC TOOL IN MEDICAL APPLICATIONS

An exhaustive list of references is not provided here and the reader is directed to the cited publications where earlier works in that area have already been referred to. The main intention is to give an insight into LCT's wide range of applications.

The greatest medical application of liquid crystals is the measurement of human skin temperature. The earliest review of the use of liquid crystals in this area was by Portnoy.[28] He reported the use of liquid crystals to examine skin temperature after the injection of drugs, identify tumor sites and to determine the success of vein grafts, among other early applications. The increased use of LCT is reflected by its inclusion in a number of recent reviews of temperature measurement methods (e.g. Refs. 29–32). As far as the author is aware, only one bibliography of medically related works has been produced,[33] in which more than a hundred publications and patents have been cited.

The simplest application of liquid crystals in the medical field is as a forehead/fever thermometer. Such a device has been recommended[34] for continuous monitoring of patient temperature in hospital emergency departments; patients developing fever after admission (which may have been missed by routine single-temperature measurements on admission) can be easily identified. In an evaluation of forehead LCT in adults, during rapid changes in core temperature, LCT results closely agreed with distal esophageal temperature whereas rectal and axillary skin temperature did not.[25]

LCT has also been reported to be superior to axillary monitoring in estimating oral temperature in children.[24] In a review of temperature measurements in newborn children,[32] LCT was deemed inadequate as a fever indicator but satisfactory as a screening tool. More recently, the TLC thermometer was recommended as an alternative to MIG thermometers for the detection of fever and hyperthermia[35] although the TLC thermometer was found to be less accurate. Another study[36] found that LCT overestimated hyperthermia and was only useful for monitoring temperature trends. The usefulness and reliability of TLC thermometers is thus still debatable. The outcomes of some investigations might have been more conclusive in favor of LCT if thermometers with better thermal resolution had been employed. Commercially available TLC thermometers have resolutions typically ranging from 0.1 to 2°C. Clearly, for direct comparison of methods, the TLC thermometer requires resolution comparable to that of the MIG thermometer. The calibration of the TLC thermometers is not documented in some studies despite the fact that it is well known that TLC temperature characteristics can change over long periods. For example, a downward shift in calibration up to 1°C has been observed over an 18-month period.[37]

As an aid to diagnosis, Crissey et al.[38] appear to have been the first to apply liquid crystals to the skin, providing demonstrative patterns of a subject's hands and then extending the investigation to include local skin temperature changes due to the injection of drugs[39] and spina bifida.[40] Later, the effectiveness of a treatment for arterial disorders of the fingers after exposure to cold was established using LCT.[41] LCT was found to be a useful tool in quantitatively visualizing circulatory improvement over the entire hand, which was unavailable with other measurement methods.[42] The advantage of using LCT in identifying vascular damage was demonstrated[43] by observing pre- and postoperative thermograms of the hand. LCT has also been used to indicate changes in peripheral circulation related to chronic liver disease[44] and has been found useful in demonstrating abnormal hand and foot blood flow in diabetics[45–47] and assessing radiation injuries.[48]

In investigating carpal tunnel syndrome, LCT has been shown to be effective in differentiating this condition from other neuropathies[49] but favorable quantitative reports were later criticized due to the lack of a control series.[50] Skin temperature monitored in the vicinity of tumor sites in limbs was found to be between 0.3 and 4°C warmer than the surrounding healthy tissue.[51,52] It was also observed that this effect was augmented if the site was repeatedly thermally stressed prior to the examination so that the blood supply to the tumor was well defined.[51] A similar phenomenon was reported (see Ref. 28) while examining the pathological events in arteries of the lower limbs due to a thyroid goiter. More recently, the same problem was studied by applying liquid crystals directly onto the skin over the thyroid.[53] Despite a 78% rate of correct LCT diagnoses, the technique was not sufficiently accurate for evaluation of the thyroid function, but provided a good additional study. The same laboratory later found LCT successful in screening for undescended testicles.[54] In another study, Selawry et al.[55] examined the temperatures of tumors in the head and neck. A number of lesions were found to hold temperatures up to 0.9°C higher than the surrounding skin. Similar studies were reported later by Talia et al.[56] and Ratz and Bailin[57] in diagnosing carotid artery obstruction and determining the lateral extent of cutaneous malignancies, respectively. The potential of LCT in assessing the presence, or absence, of angina has also been demonstrated.[58]

LCT has successfully demonstrated and recorded the therapeutic effect of acupuncture treatment,[59,60] including treatment in areas remote from the needle points. The use of LCT in the diagnosis of deep venous thrombosis (DVT) associated with various conditions has received both favorable[61–64] and unfavorable[65–67] reports. Asymmetry of thermal patterns representing increased temperatures and delayed response to cooling is used to indicate DVT. LCT thus provides a pain-free alternative to invasive and radioactive techniques such as venography or phlebography and the fibrinogen uptake test (FUT) (which has questionable accuracy and risk of HIV infection). In a recent comparison of LCT with venography and ultrasonic duplex scanning,[64] LCT was recommended as a cost-effective screening tool, especially where other scanning facilities are unavailable. The usefulness of LCT in postoperative monitoring of microvascular cases has also been reported (as opposed to using implanted Doppler probes or thermocouples). Venous thrombosis was revealed using TLC thermometers to indicate a 2°C temperature differential[68] with LCT now being routinely used for postoperative monitoring. Several researchers have used LCT to detect breast cancer. A comparison of LCT with infrared thermography[69] concluded that LCT can effectively detect breast cancer. In a subsequent study from the same laboratory,[70] as part of a continuing program in evaluating LCT, it was established that alcohol and smoking rendered the thermograms unreliable. Despite such influences, and those of the environment, another favorable report on the use of liquid crystals for skin temperature indication[22] led to the development of portable equipment using the technique. It was later concluded,[71,72] that LCT was suitable for detecting large, bulky tumors, but that the smaller the lesion, the less likely it would be detected. LCT was used to establish that a waiting period is necessary to allow thermal equilibrium to be achieved with the environment before reliable breast thermograms could be obtained.[73] Davison et al.[74] extended their applications to demonstrating placental location using LCT. Later, LCT was used to correctly identify the placental site in 75% of cases, during the second half of pregnancy.[75] This study concluded that LCT would be immediately of use to obstetric departments where sophisticated equipment was not yet available, and that further development of the TLC formulation would lead to improved accuracy.

A number of researchers have investigated the use of LCT in documenting subjective complaints, of pain by examining the skin temperature of the back, legs, hands, and feet. Excellent results in the diagnosis of spinal root syndromes were reported by Pochaczevsky et al.,[76] despite the fact that thermographic changes local to the spine are not necessarily associated with changes in the extremities. LCT did, however, clearly map the temperature changes. The application of LCT was later extended to identifying painful varicocele.[77] LCT has also shown promise[78] as an additional diagnostic tool in the assessment of back pain where alternative techniques may lead to falsely positive results due to previous surgery. A later study[79] reported a reduced usefulness of the technique in revealing nerve root compression in lumbosacral lateral spinal stenosis. Pain relief has also been monitored using LCT.[42,80] In a recent preliminary study,[81] LCT was applied to a subject's back as a diagnostic tool in identifying allergies, as an alternative to the common prick test. Promising results were reported due to skin temperature increases up to 4°C and the study was to be continued. Successful application of LCT to the face has also been demonstrated[82] and has aided the assessment of temporomandibular joint dysfunction.[83,84] The potential of LCT in clinical cardiology has been demonstrated by extensive experimental studies;[85–87] dynamic thermal changes in the left ventricular surface of rabbit myocardia have been quantified with a thermal resolution of $<0.015°$C. Other dentistry and veterinary applications of LCT have also been reported (see Ref. 33).

Liquid crystals have been utilized in the development of surgical equipment; for example, in a heated surgical probe, to observe the temperature field produced by the probe in tissue, as a means for predicting lesion size based on the time of application.[88] A similar investigation was completed a year later on a cryosurgical probe.[89] Devices for monitoring temperature in the larynx[90] and in the heart during open heart surgery[91] have also utilized LCT as the temperature sensor. A liquid crystal-coated contact lens has been used for the measurement of corneal surface temperatures.[92] A pressure-sensitive device has been developed[93] to assist patients with loss of hand pressure sense to prevent further damage to the hands. A liquid crystal optical fiber temperature probe has been used to measure blood flow in the coronary sinus.[94] Although not used for medical applications, a linear displacement sensor using a liquid crystal cell has been proposed[95] and later, a velocity indicator to determine flow rate based on the velocity being proportional to temperature change was proposed,[96] as well as displacement and pressure transducers.[97,98] LCT has also been employed in indicating radiation leakage.[99,100]

Finally, despite the wide use of liquid crystals in engineering to indicate convective heat transfer coefficients, shear stress, skin friction, and general boundary layer visualization, relatively little work has been completed that is directly relevant to biomechanics. Noon[101] points out how flow studies have influenced the development of techniques of vascular anastomosis and cardiac valves. The aforementioned work of Swanson and Wingard[87] demonstrated the use of LCT in convective heat transfer studies in biomechanics. Water-resistant sprayable liquid crystal formulations are now available which further extend their applications, even to blood or its analogues; for example, visualization of boundary layer separation and transition in water[102,103] and the suspension of liquid crystals in water–glycerol for simultaneous velocity and temperature indication[104] could both be useful in biomedical studies.

Much of the work in this area has been published only in the engineering domain. Wider dissemination is now needed in the biomedical field to draw engineers and medics together to fully exploit the potential of liquid crystal materials, especially considering the recent advances in experimental techniques. The use of video cameras with image processing allows both steady and pulsatile/time-dependent situations to be examined. Besides the continued pursuit of work reported here, other possible biomedical applications, either directly to tissue or on experimental models, include thermal investigations related to orthopedics and dentistry; strains generated by orthopedic implants; indication of flow separation, reattachment, stagnation and heat transfer in prosthetic heart valves, bends, arterial bifurcations, stenosed arteries, or any arterial system. In addition, LCT could be used to obtain benchmark experimental data which would validate numerical predictions. With further development, liquid crystals could also provide a quantitative indication of skin friction/shear stress. It has been suggested[86] that liquid crystals might serve as substrates for cells in tissue culture and biopsy samples which would allow cancerous cells to be identified by their different metabolic heat generation.

6 CONCLUDING REMARKS

The principles and practice of liquid crystal thermography have been described with particular reference to interpretation and calibration methods and the advantages and limitations of using liquid crystals as a surface temperature indicator. Particular attention has been paid to the measurement of skin temperature. Medical applications of LCT over the past 30 years have been reviewed and, based on this review, the potential of LCT in various medical-related applications has been assessed. By indicating thermal asymmetry in the body or localized hot or cold regions, LCT has proved useful in indicating significant cancerous, vascular disease and spinal conditions, among others. In general LCT has been recommended as an initial safe screening tool as an alternative to more expensive and/or painful diagnostic techniques such as infrared thermography, duplex scanning, venography, or FUT, but its use in direct diagnosis of physical conditions remains debatable. At present it provides a valuable aid to conventional diagnosis techniques since temperature differences can be due to a number of conditions; for example, warmth in the leg could be due to fracture, local infection, arthritis, DVT and so on, and LCT is therefore nonspecific. Differences in human interpretation of the colors exhibited by LCT have been common in the literature reviewed. In the engineering domain, however, this subjective interpretation of color has now been eliminated (including effects due to curvature), leading to improved thermal and spatial resolution and accuracy.

LCT is an excellent method for monitoring trends in temperature changes and may be useful for this purpose, for example, during surgery, postanesthetic care, pre- and postoperative monitoring, or in accident and emergency departments. It is relatively inexpensive, reversible, repeatable, sensitive, easy to use, and convenient; manual processing allows the technique to be used at the bedside. It is noninvasive, painless, and involves no radiation exposure. In general, the advantages of LCT far outweigh its limitations.

The adoption of a multidisciplinary research approach is essential to the successful development and application of biomedical-related technologies. This overview will, hopefully, stimulate interest in using liquid crystal materials to aid medical diagnosis and the development of temperature monitoring equipment. Its potential certainly warrants its evaluation against other diagnostic methods.

Acknowledgments

The author would like to thank Mrs. D. Corlett for maintaining the liquid crystal database and Hallcrest Ltd. (Poole, UK) for permission to partly reproduce figures from Ref. 3.

APPENDIX A

As well as private communications, the following commercial sources are used to establish the liquid crystal thermography database:

Engineering Index On-line/Compendex CD-Rom
Inspec CD-Rom
NTIS Government Reports On-line
BIDS: British Library Inside Information
  Index of Scientific and Technical Proceedings
  Science Citation Index
MEDLINE(R) National Library of Medicine's bibliographic database
NIOSHTIC(R) US Occupational Safety and Health database
HSELINE Health and Safety Executive Library and Information Service.

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